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Green Hydrogen Powered Forklifts in Industrial Transport: Case Study of an Italian Fruit and Vegetable Market

Simone Pedrazzi*, Enrico Morini, Marika Nasti, Simone Pizzileo, Giulio Allesina

University of Modena and Reggio Emilia, Department of Engineering "Enzo Ferrari", Via Vivarelli 10/1, 41125 Modena, Italy

Corresponding Author Email: simone.pedrazzi@unimore.it

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ABSTRACT

In a scenario where there is a tendency to continuous processes to reduce dependence on carbon energy, hydrogen is an emerging, efficient, and highly sustainable choice. In particular, in the field of application, the fuel cell is among the most promising technologies, protagonist, in recent years, of technological advances such as to make it an absolutely valid choice for the production of clean energy. This study lays the basis for a new concept of sustainable industry proposing an energy solution interacting between solar production and equipment for the handling of materials powered by fuel cells. In this context, the main objectives are related to the reduction of CO_2 emissions, to limit downtime and pursue a streamlining of the management and distribution of goods within a fruit and vegetable market in southern Italy. The proposed method consists in the installation of a photovoltaic system to cover the energy needs, including the electricity demand for the use of forklifts powered using green hydrogen. This investment is closely linked to a smart management of the industrial sector, able to offer different advantages over the use of other technologies in terms of energy and environmental sustainability and safety. The proposed configuration has a 454.3 kWp photovoltaic system divided into 59 sub-installations of 7.7 kWp each, each of them is capable to produce enough energy for the production of green hydrogen need to fuel a forklift for an entire year.

1. INTRODUCTION

In recent decades the world scenario has undergone major changes aided by the climate change emergency. The difficulty to deal with it and the policy going towards a continuous increase in efficiency [1]. In particular, UE has defined a policy plan to reduce energy consumption and waste by at least 32.5% up to 2030 by requiring the adoption of techniques designed to achieve a sustainable energy supply that meets the targets imposed by Member States, to reduce the costs of foreign energy imports and to promote European competitiveness [2].

This action plan has introduced important and binding measures for Europe, but the current Italian scenario shows a strong dependence on imports of fossil fuels, making it vulnerable from the point of view of energy security. The need to test a functional and flexible system requires citizens to increase the use of renewable sources by planning integrated systems to respond to an increasing demand for energy and to face the difficulties due to a displacement of production on the territory, burdening the resilience of the objectives stated in 2030 Sustainable Development Agenda [3].

Despite the fact that Northern Italy has a greater industrial deployment, the natural resources are located mostly in the South of Italy and represent the engine of the whole sustainable chain. On this way, the idea of an increasingly widespread production of energy from renewable sources throughout the territory takes on greater strategic importance: the Southern regions contribute in an important way in terms of RES power covering 87% of the entire wind power production and 50% of the photovoltaic power production, highlighting a significant difference between the most energy-intensive northern regions and the South, country's energy reserve [4]. Nowadays, the great Italian productive activities are the engine of the country's economy, but they are often managed in a less sustainable way.

The purpose of this study is to give more energy independence to a fruit and vegetable market in Southern Italy from a sustainable and economic point of view, thanks to a strategic use of renewable resources. The market is located at Pagani in the Campania region. This region standing among the top 10 Italian regions for more installed photovoltaic power, preceded only by wind energy for the production of electricity.

The idea that will be presented in this paper is based on two integrated systems having as starting point the production of energy from the solar source. The total electricity production is due to:

- The refrigeration of the products (Materials and Method, System I);
- The use of 59 forklift trucks, used to transport and distribute goods (Materials and Method, System II).

The System 1 has to fulfil the total energy needed by the market activities, thus a 249.6 kWp PV plant is installed to cover the 59 fruit and vegetable companies and the auxiliaries services.

The main energy-consuming activities, responsible of a high impact on energy cost, can be summarized with products refrigeration and conservation operations, cold rooms power and light in workspaces.

According to that, the planning proposed in this paper is based on a 316832 kWp annual consumption completely covered by the PV plant.

On the one hand, with regard to the System II, the design presented in a previous paper [5] considered a 2.8 kWp PV plant for each of the 59 electric forklift trucks charger. This design ensures enough electricity to satisfy forklift annual consumption during the 1659 hours of work. On the other hand, the current project tries to replace electric battery powering with hydrogen fuel cells.

Especially in the industry, there is a tendency to develop decarbonisation processes that contrast with the exponential demand for electricity [6]. On this way, the use of fuel cells implemented in forklifts trucks could be a possible solution that allows the reduction of CO_2 emissions and also charging times [7].

Despite the electric forklift trucks allow a CO_2 emissions drastic reduction, the charging time are of 13/14 hours. This setting particularly disadvantages users with highly hard work shifts, leading to the inclusion of batteries replacement processes: it implies a working activities complication, a management costs increase and a productivity decline [8].

As a result, this study suggests a system based on hydrogen fuel cells technology in order to be more efficient in terms of charging time and able to be as sustainable as electric forklift trucks [8, 9]. According to this, the proposal provides an electrolysis process for the conversion of hydrogen from H_2O molecules that allows, among other things, an easier management thanks to low operating temperatures [10]; the ambition of this solution is expressed in the fact that the process of electrolysis is powered by the photovoltaic System II in order to produce green hydrogen. The use of hydrogen forklift trucks ensures:

- *Greater sustainability and safety* because green hydrogen is produced by drastically reducing carbon dioxide emission: the fuel cells convert H_2 into water thanks to the air oxygen producing electricity without the use of chargers;
- *Increasing productivity* due to forklift charging times of around 2-3 minutes;
- *Greater flexibility and versatility* because the refueling can be done independently from solar production, regardless of temperature conditions and the fuel cells are also applicable in existing trucks.

Therefore, this study focuses on three fronts:

- Compliance with a model that sets goals for global *energy sustainability*;
- The drastic *decrease in* CO_2 *emission* in the industry due to the use of carbon neutral technologies.
- The important *increase in productivity and distribution* within a commercial exercise of large proportions linked to transport vehicles charging times much lower than other solutions.

2. MATERIALS AND METHODS

2.1 PV plants configurations

The study presented in this paper is developed from the installation of a 703.9 kWp photovoltaic system in the service of *Mercato Ortofrutticolo Nocera-Pagani (Salerno)* common consumption: it extends across 13 ha in the Agro Nocerino Sarnese, and it represents a central point in the fruits and vegetables' business of Southern Italy. The total configuration is based on the installation of an integrated system composed by:

- 249.6 kWp PV system designed to give energy for the market activities and auxiliaries (System I, [5]);
- 454.3 kWp PV system designed to fulfil the H_2 fuel cells forklift trucks recharge (System II).

If system 1 is configured to meet the energy demands from internal market activities, as regards System 2 the study focuses on the shifts worked by each company in the market: the goal, in fact, is to appropriately size the photovoltaic system to meet the charging cycles of each H_2 fuel cells forklift trucks and allow an optimal use by improving the distribution of products within the market.

In relation to the current market organization, the work of a forklift associated with each of the 59 stores in the market area has been taken into account, providing the same number of charging stations for vehicles in an entirely redeveloped area of the same market.

As shown in the Figure 1, the building C represents the cover of the parking lot for the employees of the market: the project presented below redevelops this structure so that it can become parking and charging station for the forklifts.

The feasibility of this project is backed up by the fact that the market is located in a position to ensure the necessary contribution of solar energy that has been estimated thanks to the use of three different software: PV-Syst^R, Meteonorm^R and S.O.L.E.^{R}.

Among them the first was used to quantify the solar radiation available on a flat plate installed in this location (1577.2 kWh/m^2), Meteonorm^R was useful to evaluate the solar path just in order to compute the most efficient inclination of solar panels according to vary season and the software S.O.L.E. has allowed us to make the most appropriate considerations regarding the shading analysis panels each other [11].

Finally, to properly study the solar plant coupled with forklift trucks, an analysis was conducted on the average monthly energy demand of each medium, in order to understand the autonomy of the same and to appropriately size the photovoltaic system connected to charging stations.

Everything is computed by assuming a daily working period from 04:00 to 12:00.

By proceeding with the dimensioning of the systems, an oversizing is decided in order to have productiveness always higher than consumption in a long planning period.

This assessment has been made to act in favor of the economic sustainability of the plant's total investment.

Figure 1. Location and elevation profile (Google Earth image)

2.2 Hydrogen fuel cell system (System II)

The amount of energy needed to overcome the use of 59 forklift trucks with fuel cell technology is entirely managed by system 2 which PV-plant is placed the construction C shown in Figure 1. Electrical PV system layout is depicted in Figure 2.

This configuration is particularly favorable compared to the management of traffic and spaces within the market area as it is possible to use the stables of forklift trucks as charging stations.

The 454.3 kWp photovoltaic system, installed on the roof of the forklifts garage, will produce the electric energy needed by the electrolyzer for the production of Green Hydrogen. The aim of this work is to replace the forklift actually used in the market with new forklift (Toyota Industries Corporation) based on Fuel Cells that use hydrogen as fuel and oxygen as oxidizer.

The idea comes from the fact that in recent years the fuel cells technology has improved faster and faster as the research and the PEMFC (Proton Exchange Membrane Fuel Cell) has now reached a good efficiency and a valuable number of production. Starting from the PV Plant electrical energy production, it has been possible to estimate the quantity of hydrogen that can be produced through the electrolyzer, and then, taking into account the period with the highest electricity production, the volumes of the hydrogen storage has been estimated. Hence, System 2 will be a Solar-Hydrogen Hybrid System, where electricity is used to produce hydrogen, sized in this way:

- from sunrise to 12:00, when the forklift trucks are in use, the solar energy produced by the photovoltaic system will be fed into the grid, thus obtaining a financial return from the sale of this energy.
- from 12:00 to sunset the energy produced by the photovoltaic system will be sent to the electrolyser and will be used to instantly produce hydrogen, which will be used directly to recharge the forklifts.

This configuration makes it possible to avoid the use of hydrogen storage systems, which would have introduced further losses in efficiency and increased the costs of the entire system.

The above has been summarized in the diagram in Figure 3 where the efficiency of the electrical production cycle can be seen starting from the photovoltaic system installed on the roof of building C up to the final destination of use represented by the 59 forklifts.

In particular, the diagram in Figure 4 represents the forklift configuration as the intended use of the project so far. The technology present in the fuel cell forklifts is robust so the intentions set out in this article are to combine a proven model within a photovoltaic system at the service of the market with the aim of drastically reduce consumption and improve transport operations and management of goods within the market area.

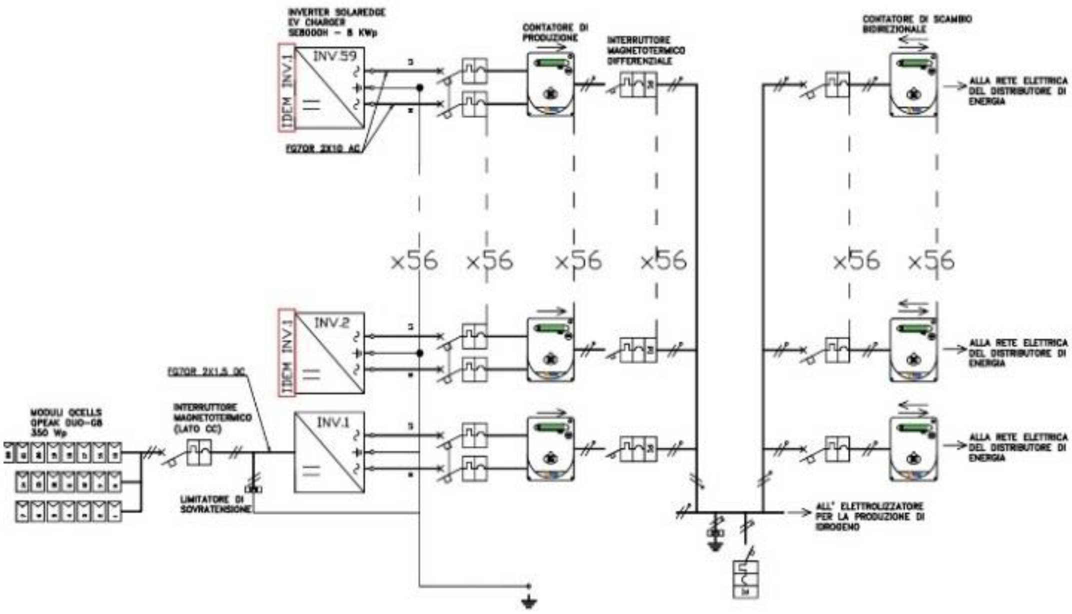

Figure 2. Single-line diagram for private consumption

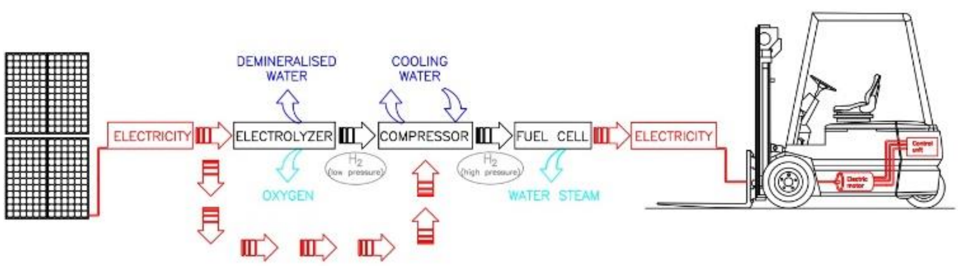

Figure 3. Design layout

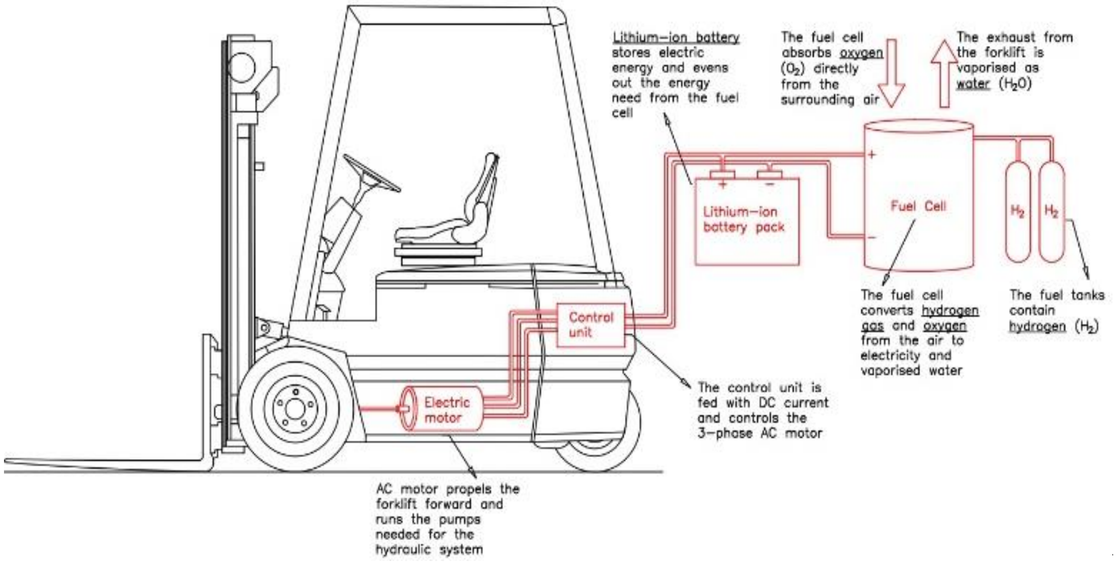

Figure 4. Fuel cell forklift scheme

3. RESULTS AND DISCUSSION

3.1 System II design results

All of the following considerations have been appropriately overestimated to allow for long-term project sustainability:

- to calculate the weight of hydrogen required for fuel cell operation, a cell power of 2.41 kW was assumed, taking into account 1659 hours/year of use and an average consumption of 4000 kWh;
- assuming a fuel cell efficiency of 50% [12, 13], the volumetric flow rate of hydrogen is 1.36 Nm^3/h at standard temperature and pressure conditions (273.15 K and 1.01325 bar). This allowed the calculation of the volume occupied by the updated hydrogen at operating conditions of 293.15 K and 700 bar, equal to 0.0021 Nm^3/h, so 2256.24 Nm^3 for one year of operation. This value, infect, is necessary for the selection of the type of lift truck and the hydrogen storage cylinders assembled.
- For an efficiency of 65% of the electrolyser [12, 13] and for the environmental conditions previously stated for the compressor, a total electrical consumption of 13823 kWh is estimated, divided into 11% for the compressor and 89% for the hydrogen production by electrolysis.
- Therefore, the solution proposed here involves a 7.7 kWp photovoltaic system to cover the energy needs of each of the 59 forklifts operating in the market area.

In order to limit the difficulty of the small space available for the installation of the modules, the configuration adopted for this system involves the choice of a string of 22 monocrystalline panels in series Qcells Q. Peak Duo-G8 350 Wp inclined by 30° and positioned on the flat surface of the indoor parking C. The latter, although having the same orientation as buildings A and B, has a usable surface not sufficient to fit all strings, therefore the favourable inclination of the modules allows an increase of the nominal power of the system capable of completely satisfying the energy demand coming from all the forklifts.

The reason for this choice is that this technology ensures a nominal output of at least 98% during the first year, 93.1% after 10 years and 85% after 25 years, thus limiting the annual degradation to a maximum of 0.54%.

It was possible to upgrade the indoor parking (previously used as parking for private cars of the employees of the market) as night storage and as charging station for forklift trucks thanks to the connection of each string with a single-phase inverter SolaredgeHD Wave SE8000H.

The power of each appropriately oversized sub plant is 7.7 kWp. In view of an annual energy balance, the study proposed in this article is based on the production of the electricity needed to generate 2256 Nm^3 of hydrogen.

The forklifts with fuel cell technology chosen have a hydrogen fuel capacity of 13.4 Nm^3: according to the electricity production linked to the availability of solar energy and the estimates in this study, each forklift would fill about half of the entire tank for intensive shift use [13, 14].

Therefore, this solution ensures a flexible use of the transport means, as despite the variability of production during the year, it is possible to use a reserve volume compared to the minimum needed for each working day. Figure 5 and 6 depicts the rendering of the PV plants on the top of the building. Figure 7 reports the monthly electrical energy production of a single PV plant, instead Figure 8 shows the Sankey diagram related to annual energy balance of a single PV plant.

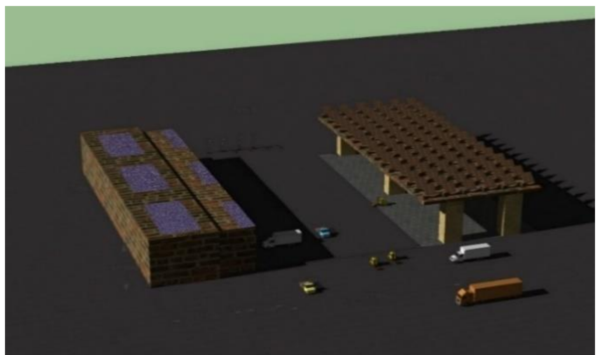

Figure 5. Rendering of photovoltaic panels on roofs A, B and C (N-E view, summer morning)

Figure 6. Rendering of photovoltaic panels on roofs A, B and C (N-W view, summer morning)

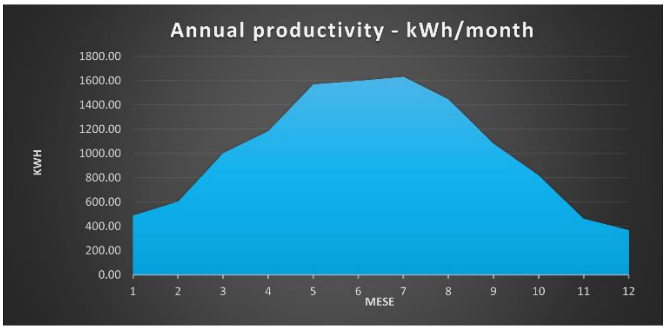

Figure 7. Single 7.7 kWp PV plant productivity - kWh/month

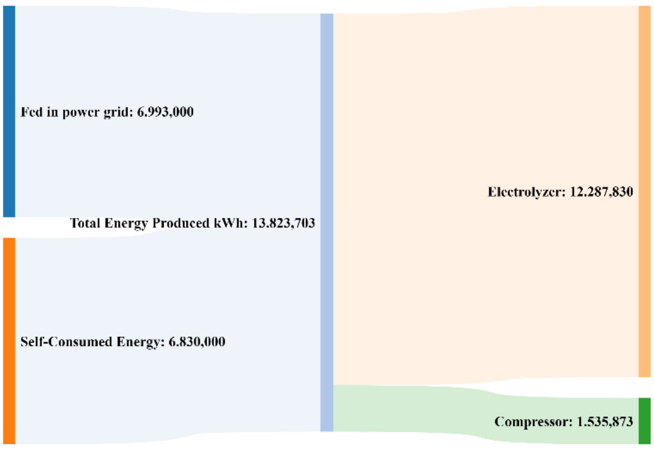

Figure 8. Sankey diagram refereed to the energy balance of a single 7.7 kWp PV power plant

3.2 Economic considerations

In addition to the above, in order to take advantage of economic incentives, it has been decided to consider each of the 7.7 kWp sub-plants as an energy community: from the point of view of reducing energy costs on the part of consumers and greater earnings from the energy produced by producers, it is of fundamental importance to provide incentives for locally shared energy.

For this reason, it was decided to refer to the economic contributions provided by the GSE [15] to remunerate the instantaneously self-consumed energy, divided as follows:

- 110 €/MWh for self-consumed energy as a premium rate;
- 70 €/MWh for energy fed into the grid as a premium rate;
- 8 €/MWh for energy communities as a unit fee.

Sharing energy with the public grid saves on transformation losses and energy transport to the grid, ensuring economic soundness to the proposed project and confirming its sustainability.

Considering the plants as small energy communities is necessary to overcome the difficulties for the coverage of electricity needs: in fact, the only photovoltaic production would be insufficient and not compatible in the context of the case study for space and economic sustainability.

The choice of combining the two solutions is ideal not only to respond perfectly to the energy demand for the production of hydrogen needed to power the fuel cells of forklifts but also to preserve the long-term viability of the project from the energy, economic and environmental point of view. According to this, the average economic saving for each installed sub-plant has been calculated with regard to the energy self-consumed and fed into the public network. According to the assumptions made underlying this study:

- from sunrise to 12:00 noon, an average annual producibility of 6.993 MWh is expected, totally fed into the public power grid;
- from 12:00 to sunset an annual average producibility of 6.831 MWh is foreseen, totally supplied to the electrolytic process for the production of hydrogen to allow the feeding of fuel cells.

Taking into account the tariffs proposed by GSE you would get annual incentives for each forklift of about 1300 €, for a total of 76700 € per year for the entire plant.

As it has clearly emerged from the pages of this paper, the main objective of this project is to think and realize a new conception of a fruit and vegetable market, where everything is thought to be sustainable from the environmental, energy and economic.

The idea is to intervene on the main consumption of electricity used in the market, through solar panels which help to reduce the balance of CO_2 emissions in the various processes of the market itself.

Compared to the solution already configured [5] centered on a photovoltaic system serving 59 sub-installations of 2.8 kW that power as many electric forklifts, this solution is more sustainable from an environmental and energy point of view but economically still immature.

The chain that leads to the production of hydrogen drags a series of energy losses that lead to a significant increase in the peak power of the photovoltaic system at the service inducing the system to be not perfectly compatible with the standards of economic sustainability.

With the further development of hydrogen fueling technologies and in anticipation of more competitive prices, it will be possible to develop efficient, robust and sustainable solutions.

4. CONCLUSIONS

The choice to build a photovoltaic system at the service of a fruit and vegetable market in Southern Italy comes from the analysis of the potential of the renewable source.

The geographical area under study has favorable conditions for the exploitation of the photovoltaic system boasting a solar radiation of 1577.4 kWp/m^2 that allows a many hours-long consistent productiveness of the day for a long period of the year. This justifies the economic sustainability of the project, which ensures a significant profit closely linked to the availability of the source thanks to the optimal use of renewable energy. Therefore, this advantage has been exploited in the design to:

- obtain substantial green electricity production which could satisfy the needs of a pivotal commercial center in the area (System 1 [5]);
- drastically reduce pollutant emissions from the use of forklifts previously fueled by fossil fuel;
- highlight the prestige of a commercial crossroads in the agri-food sector, proposing it as an example of a turning point in zero-emission industries.

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